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(54) **SYSTEMS AND METHODS FOR IMPROVING THE QUALITY OF IMAGES IN A PET SCAN**

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(57) **ABSTRACT**

Systems, devices and methods of reconstructing an image from a positron emission tomography scan that may include detecting a plurality of photons selected from scattered photons and unscattered photons by a plurality of detectors, identifying a time interval for each of the plurality of photons by a processing device, matching each of the plurality of photons into a plurality of pairs of coincident photons based upon a substantially simultaneous time interval identified by the processing device, measuring an energy produced by each of the plurality of photons by the plurality of detectors, determining a scattering angle for each pair of coincident photons from an annihilation point relative to the position of the plurality of detectors by the processing device based on the energy produced and reconstructing an image using a reconstruction algorithm, wherein the reconstruction algorithm uses the scattering angle of each pair of coincident photons.

29 Claims, 8 Drawing Sheets
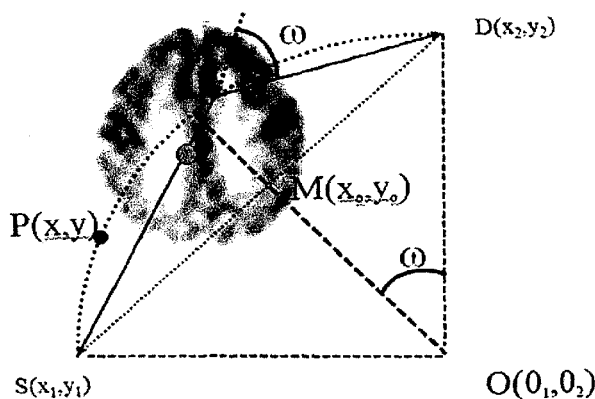
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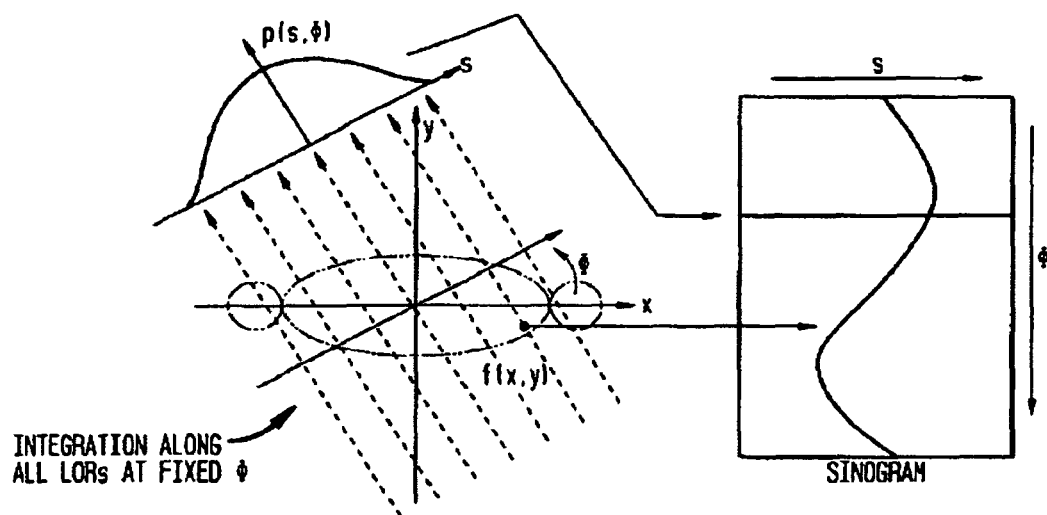Zaidi, H., et al., "Strategies for attenuation compensation in neurological PET studies," Neuroimage, vol. 34, No. 2, pp. 518-541 (2007).
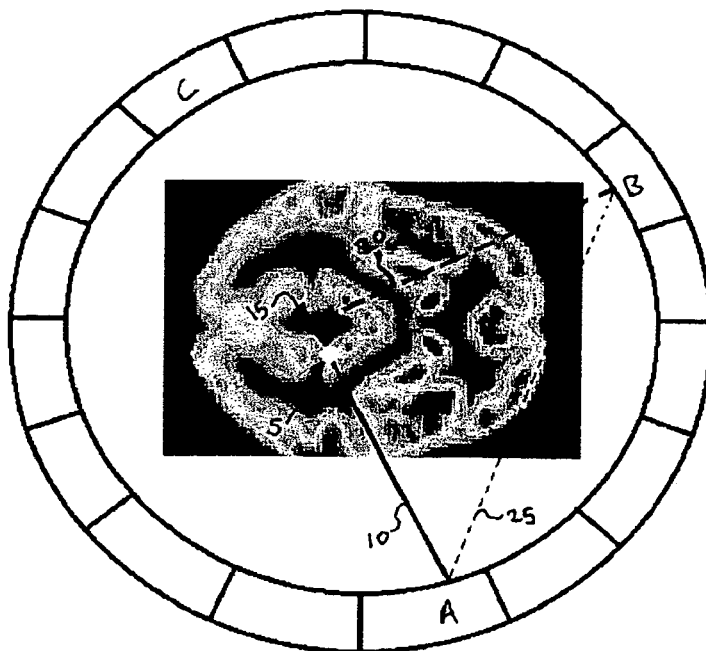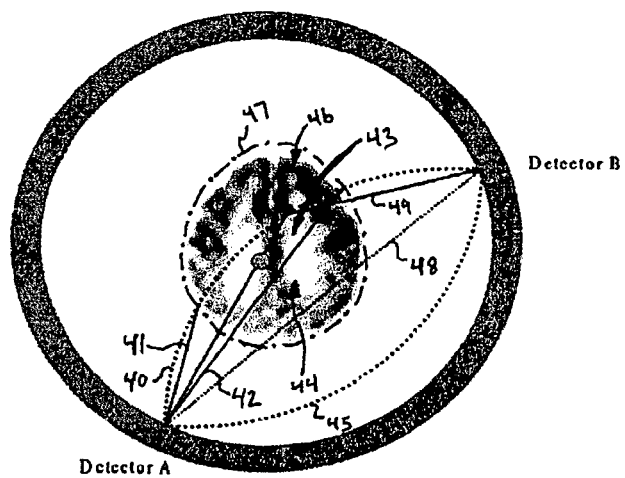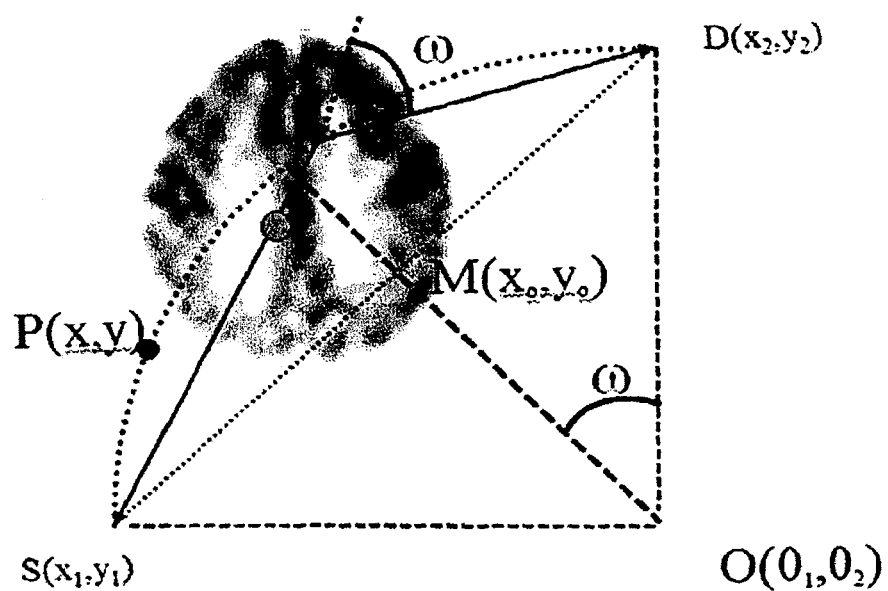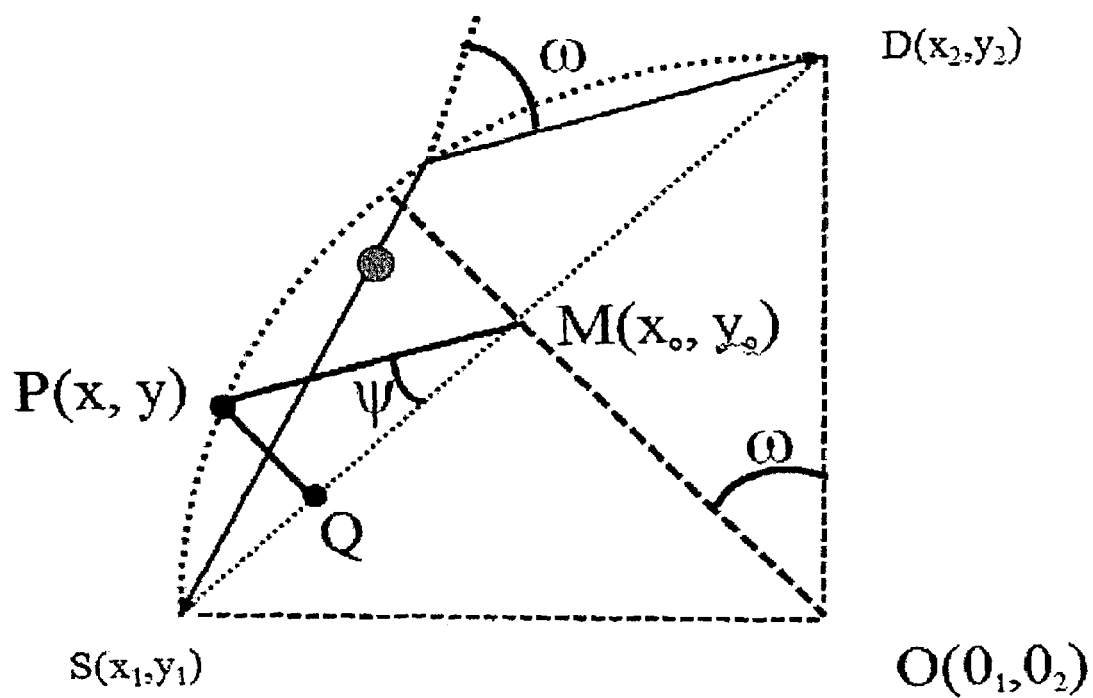
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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 5

FIG. 6

Position detectors — 105

Record location of detectors — 110

Detect incoming photons — 115

Record photon information — 120

Are detected photons coincident? — 125

No → Reposition detectors and record new positioning — 130

Yes

Retrieve measured photon energies from memory — 135

Initialize image matrix — 140

Calculate the scattering angle for each pair of photons — 145

Identify circular arcs for each pair of photons — 150

Construct a boundary line around the subject's body — 152

Construct lines from detected unscattered photon to intersection of circular arcs and boundary line around subject's body — 153

Identify annihilation area — 155

Use reconstruction algorithm — 160

Normalize and back-project to a ratio matrix — 165

Update image — 175
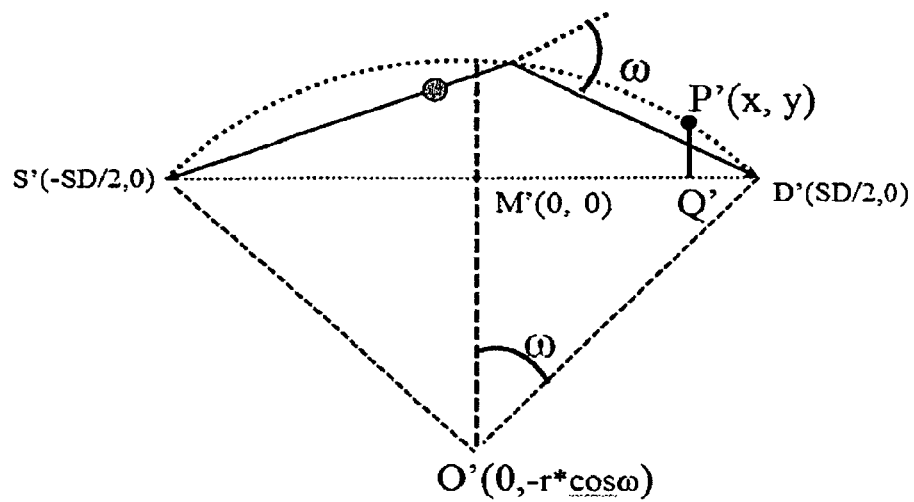
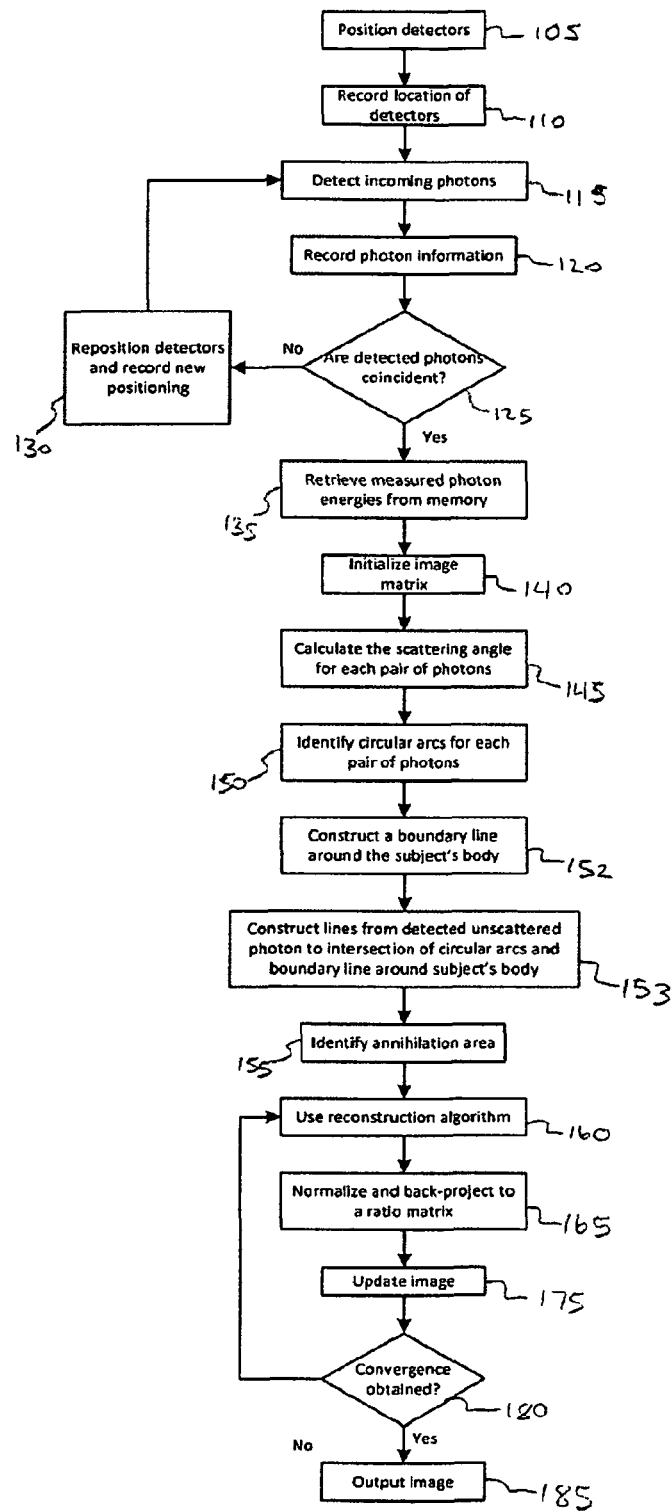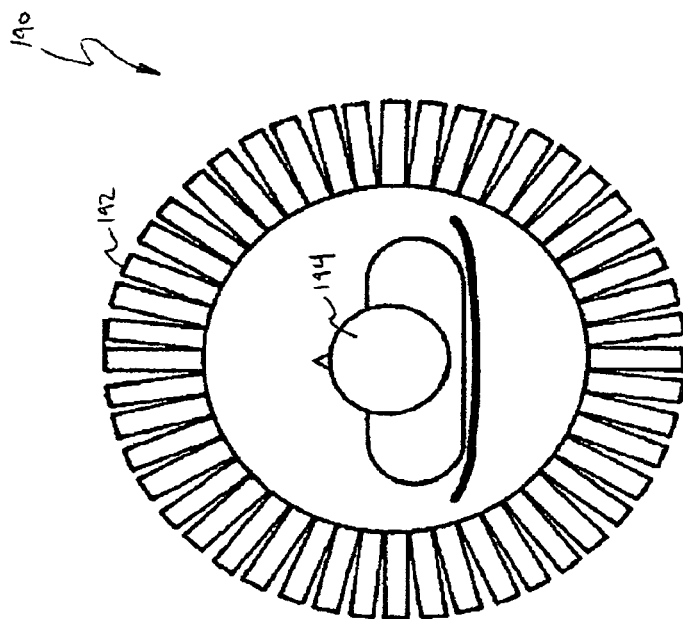Convergence obtained? — 180

No

Yes

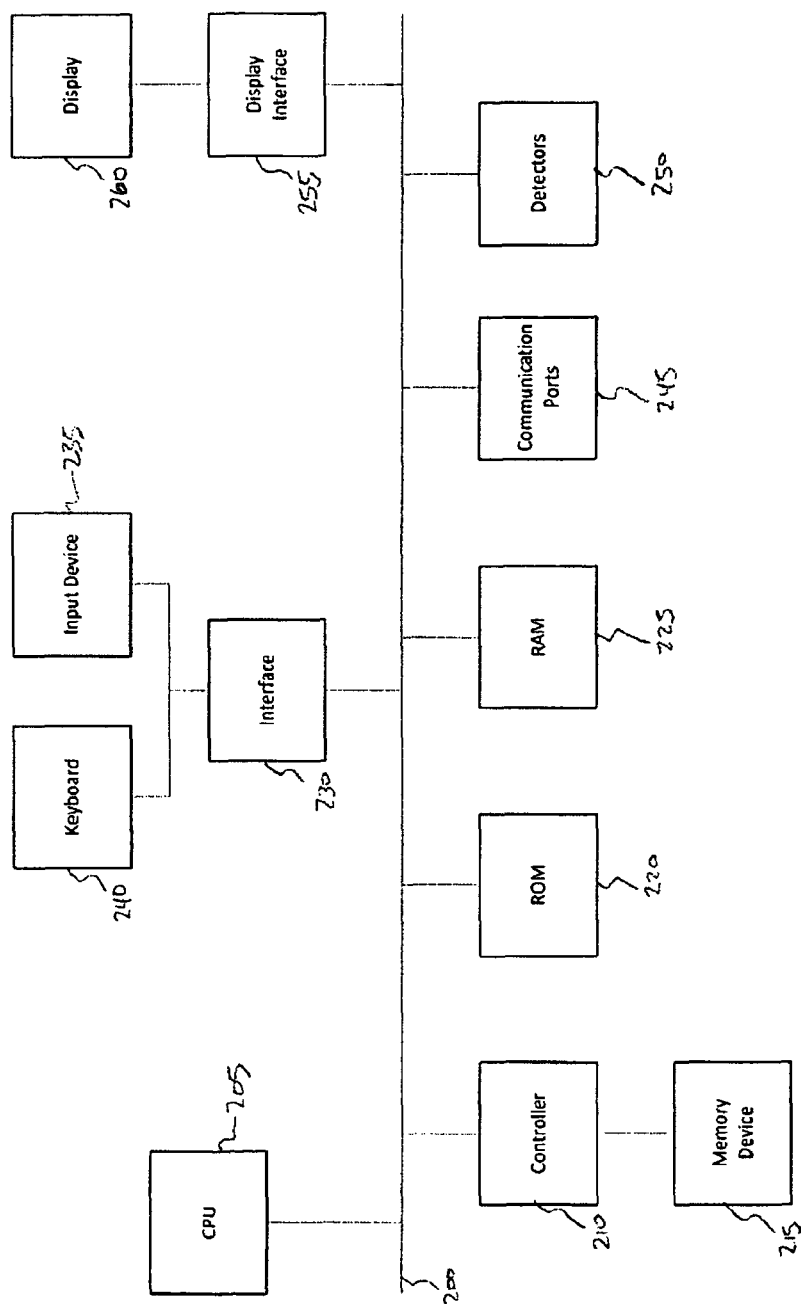Output image — 185

FIG. 7

FIG. 8

FIG. 9

SYSTEMS AND METHODS FOR IMPROVING THE QUALITY OF IMAGES IN A PET SCAN

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application is continuation under 35 U.S.C. §120 of U.S. patent application Ser. No. 13/977,893, titled "Systems and Methods for Improving the Quality of Images in a Pet Scan" filed on Jul. 1, 2013, now U.S. Pat. No 8,866,087, which is a U.S. national stage application under 35 U.S.C. §371 of International Application No. PCT/CA2012/050352, filed on May 29, 2012, which are both incorporated herein by reference in their entirety.

BACKGROUND

In Positron Emission Tomography (PET) systems, particularly those used for scanning small animals and those that construct 3-dimensional images, scattered photons play a significant role because they comprise a large portion of the total number of photons scanned and are the primary contributor to reduced contrast and quantitative accuracy, which leads to poor image reconstruction during the PET scan. 3-dimensional (3D) PET systems are particularly sensitive to scattered photons, and as a result, the PET images appear blurred or contain artifacts.

Previous efforts to eliminate or otherwise minimize the blurring and quantitative inaccuracy created by scattered photons has generally included considerable preprocessing of data and the administration of higher dosages of radioactive material to the subject.

Thus, there exists a need for systems and methods for reducing PET systems' sensitivity to the presence of scattered photons, thereby allowing for more photon data to be used in reconstructing an image, which in turn improves signal-to-noise ratio and the contrast recovery coefficient in PET scanning systems and reduces the amount of radioactive material administered to the subject.

SUMMARY

In an embodiment, a method of reconstructing an image from a positron emission tomography scan may include detecting a plurality of photons selected from scattered photons and unscattered photons by a plurality of detectors, identifying a time interval for each of the plurality of photons by a processing device, matching each of the plurality of photons into a plurality of pairs of coincident photons based upon a substantially simultaneous time interval identified by the processing device, measuring an energy produced by each of the plurality of photons by the plurality of detectors, determining a scattering angle for each pair of coincident photons from an annihilation point relative to the position of the plurality of detectors by the processing device based on the energy produced and reconstructing an image using a reconstruction algorithm, wherein the reconstruction algorithm uses the scattering angle of each pair of coincident photons.

In an embodiment, a method of reconstructing an image from a positron emission tomography scan may include detecting a plurality of photons selected from scattered photons and unscattered photons by a plurality of detectors, identifying a time interval for each of the plurality of photons by a processing device, matching each of the plurality of photons into a plurality of pairs of coincident

photons based upon a substantially simultaneous time interval identified by the processing device, measuring an energy produced by each of the plurality of photons by the plurality of detectors, calculating a first circular arc created by all possible positions of a photon of a pair of coincident photons based on the energy produced by the photon by the processing device, calculating a second circular arc created by all possible positions of the photon based on the energy produced by the photon by the processing device, constructing an outline of a subject, constructing one or more lines from a point of detection of one of the unscattered photons to each intersection of the outline of the subject with the first circular arc or the second circular arc, identifying an annihilation area bounded by two or more of the following: the one or more lines, the first circular arc, the second circular arc, and the outline of the subject, identifying the plurality of possible locations of the annihilation point within the annihilation area, based on the energy produced, determining a scattering angle for each pair of coincident photons from a location of the annihilation point relative to the position of the plurality of detectors by the processing device and reconstructing an image using a reconstruction algorithm, wherein the reconstruction algorithm uses the scattering angle of each pair of coincident photons.

In an embodiment, a system for use in reconstructing an image from a positron emission tomography scan may include a processing device and a non-transitory computer-readable storage medium in communication with the processing device, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, cause the processing device to detect a plurality of photons selected from scattered photons and unscattered photons, identify a time interval for each of the plurality of photons, match each of the plurality of photons into a plurality of pairs of coincident photons based upon a substantially simultaneous time interval identified, measure an energy produced by each of the plurality of photons, determine a scattering angle for each pair of coincident photons from an annihilation point relative to the position of the plurality of detectors based on the energy produced, measure an energy produced by a plurality of scattered photons from an annihilation event, match a plurality of pairs of coincident scattered photons based upon the energy measured, determine a scattering angle of each pair of coincident scattered photons from the plurality of pairs of coincident scattered photons and reconstruct an image using a reconstruction algorithm, wherein the reconstruction algorithm uses the scattering angle of each pair of coincident scattered photons.

In an embodiment, a positron emission tomography scanner may have a plurality of detectors, a processing device in operable communication with the plurality of detectors and a non-transitory computer-readable storage medium in communication with the processing device, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, cause the processing device to direct the plurality of detectors to detect a plurality of photons selected from scattered photons and unscattered photons, identify a time interval for each of the plurality of photons, match each of the plurality of photons into a plurality of pairs of coincident photons based upon a substantially simultaneous time interval identified, direct the plurality of detectors to measure an energy produced by each of the plurality of photons, based on the energy produced, determine a scattering angle for each pair of coincident photons from an annihilation point relative to the position of the plurality of detectors and reconstruct an image using a

reconstruction algorithm, wherein the reconstruction algorithm uses the scattering angle of each pair of coincident photons.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** depicts a diagram illustrating a relationship between a PET projection and a sinogram.

FIG. **2** depicts a diagram illustrating a single scatter model for PET imaging using a plurality of detectors arrange in a ring format, in accordance with an embodiment.

FIG. **3** depicts a diagram of the two arcs created by the PET system in response to detecting a single scatter event according to an embodiment.

FIG. **4** depicts a graphical diagram of measuring a circular arc from a single scatter model according to an embodiment.

FIG. **5** depicts an alternative graphical diagram of measuring a circular arc from a single scatter model according to another embodiment.

FIG. **6** depicts a rotated view of the graphical diagram of FIG. **5**.

FIG. **7** depicts a flow diagram of an illustrative method of reconstructing an image from a PET scan according to an embodiment.

FIG. **8** depicts an illustrative cross-sectional view of a PET system according to an embodiment.

FIG. **9** depicts a block diagram of illustrative internal hardware that may be used to contain or implement program instructions according to an embodiment.

DETAILED DESCRIPTION

This disclosure is not limited to the particular systems, devices and methods described, as these may vary. The terminology used in the description is for the purpose of describing the particular versions or embodiments only, and is not intended to limit the scope.

As used in this document, the singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. Unless defined otherwise, all technical and scientific terms used herein have the same meanings as commonly understood by one of ordinary skill in the art. Nothing in this disclosure is to be construed as an admission that the embodiments described in this disclosure are not entitled to antedate such disclosure by virtue of prior invention. As used in this document, the term "comprising" means "including, but not limited to."

The following terms shall have, for the purposes of this application, the respective meanings set forth below.

As used herein, the terms "sum," "product" and similar mathematical terms are construed broadly to include any method or algorithm in which a single datum is derived or calculated from a plurality of input data.

A "computing device" refers to a computer, a processing device and/or any other component, device or system that performs one or more operations according to one or more programming instructions. The computing device may be integrated within a PET system or may be an individually functioning unit that is in operable communication with the PET system. An illustrative computing device is described in FIG. **9**.

Also as used herein, the phrase "reconstructing an image" is not intended to exclude embodiments in which data representing an image is generated, but a viewable image is not. Therefore, as used herein, the term "image" broadly refers to both viewable images and data representing a

viewable image. However, many embodiments generate (or are configured to generate) at least one viewable image.

Additionally, while the present disclosure refers in detail to a PET system, particularly a three-dimensional PET system, those skilled in the art will recognize that other modalities such as, for example, PET/ultrasound, PET/Magnetic Resonance Imaging (PET/MRI), PET/Electron Beam CT (PET/EBCT), PET/Computed Tomography (PET/CT), Single Photon Emission Computed Tomography (SPECT) may be used without departing from the scope of the present disclosure. Additionally, systems are contemplated in both medical settings and non-medical settings such as, for example, an industrial setting or a transportation setting.

In PET imaging, a positron-emitting radionuclide is introduced into the object to be imaged via injection, inhalation, ingestion or the like. Once the positron-emitting radionuclide has been administered, its physical and bio-molecular properties cause the agent to concentrate at specific locations within the subject's body. Clinically significant factors in this distribution may include an actual spatial distribution of the radionuclide, an intensity of the region of accumulation of the radionuclide, and kinetics of the process from administration to elimination of the radionuclide. During this process, a positron emitter attached to the positron-emitting radionuclide will emit a number of positrons, which may vary according to certain physical properties of the radionuclide, such as, for example, half-life, branching ratio, and the like.

When an emitted positron collides with an electron, an annihilation event occurs, which destroys both the positron and the electron. Typically, the annihilation event will produce a pair of gamma ray photons at 511 keV, wherein the two photons generally travel in opposite directions (i.e., substantially 180 degrees apart from each other).

The PET system may utilize a plurality of detectors to detect the two photons, and then use a software program to draw a line between their respective locations (i.e., the line-of-response (LOR)) to determine a likely location of the annihilation event. While this process will only identify a single line of possible interaction, by drawing a large number of those lines from as many photons as possible, the original distribution can be estimated.

In addition to determining the location of the annihilation event, a time-of-flight (TOF) calculation also includes identifying a time coincidence between the detection of the two 511 keV gamma photons in the two oppositely disposed detectors (i.e., the photon emissions are detected substantially simultaneously by each detector).

PET systems may use the plurality of detectors positioned across from one another to detect the photons emitting from the annihilation events. In some PET systems, a ring of detectors may be used to detect photons at every possible angle. Thus, a series of scanners arranged in a substantially cylindrical manner may be used to detect as many photons as possible. In other PET systems, the scanners may be arranged in a series of partial rings that are capable of rotating about a subject to detect as many photons as possible at every possible angle.

After being sorted into parallel projections, the LORs defined by the coincidence events are used to reconstruct a three-dimensional distribution of the positron-emitting radionuclide within the subject. In two-dimensional PET systems, each 2D transverse section or "slice" of the radionuclide distribution is reconstructed independently of adjacent sections. In fully three-dimensional PET systems, the data are sorted into sets of LORs, where each set is parallel

to a particular detector angle, and therefore represents a two dimensional parallel projection p(s, φ) of the three dimensional radionuclide distribution within the subject, where s corresponds to the distance of the imaging plane perpendicular to the scanner axis and φ corresponds to the angle of the detector plane with respect to the x axis in (x, y) coordinate space. In other words, φ corresponds to a particular LOR direction. Coincidence events are integrated or collected for each LOR and stored as a sinogram. In this format, a single fixed point in f(x,y) traces a sinusoid in the sinogram. In each sinogram, there is one row containing the LORs for a particular azimuthal angle φ; each such row corresponds to a one-dimensional parallel projection of the tracer distribution at a different coordinate along the scanner axis, as shown in FIG. **1**.

An event may be registered if both detectors detect an annihilation photon within a coincidence time window τ. A pair of detectors may be sensitive only to coincidence events occurring in the volume between the two detectors, thereby eliminating the need for physical collimation, and thus significantly increasing sensitivity. Accurate corrections may be made for the self-absorption of photons within the subject (i.e., attenuation correction) so that accurate measurements of tracer concentration can be made.

The number of coincidences detected per second within a field of view (FOV) of a detector is known as the count rate of the detector. The count rate at each of two oppositely disposed detectors (e.g., detector A and detector B), may be referred to as singles counts (e.g., singles S_A and S_B). The time required for a gamma photon to travel from its point of origin to a point of detection is referred to as the time of flight (TOF) of the gamma photon. TOF is dependent upon the speed of light c and the distance traveled. A time coincidence, or coincidence event, is identified if the time difference between the arrival of signals in a pair of oppositely disposed detectors is within the coincidence time window τ. In conventional PET systems, the coincidence detection time window τ is wide enough so that an annihilation event occurring anywhere within the object would produce annihilation gamma photons reaching their respective detectors within the coincidence window. Coincidence time windows of 4.5-12 nanoseconds are common for conventional PET systems, and may be determined by the time resolution capabilities of the detectors and electronics.

Septumless PET systems, or 3D PET systems (i.e., without interplane septa) currently constitute a large percentage of the total market for PET imaging. Because of the lack of interplane septa, scattered events (i.e., annihilation photons undergoing Compton scattering before reaching the detector) may represent a large portion of the measured data (e.g., up to 50% or more in clinical studies).

As shown in FIG. **2**, the annihilation event occurring at an emission point **5** produces two oppositely traveling photons along LOR **10**. At least one of the photons, however, may undergo Compton scattering, such as the scatter of the photon at a scatter point **15**, which changes the photon travel direction to path **20**. The first photon, which remains unscattered in this instance, is detected by detector A. The second photon, which is scattered in this instance, is detected by detector B because it has been redirected off of its normal path to detector C. Thus, without the scatter correction as presented herein, the PET system would recognize the scattered photon as an unscattered photon, and would determine an incorrect LOR **25**.

In an embodiment, a system and method for measuring scattered photons and reconstructing an image based upon the measuring in a PET system is disclosed. Generally, the

system may measure the respective energies of a plurality of pairs of coincident photons and then use the measured energies to create a two arc model for each pair of coincident photons for use in image reconstruction, as shown in FIG. **3**. The two arc model may comprise a first arc **40** and a second arc **45**. Each of the arcs **40**, **45** may extend between the two detectors that measure the photons, such as in the present example, Detector A and Detector B.

Each of the arcs **40**, **45** may be a graphical representation created by the PET system that indicates all of the possible locations of a point of scatter of the scattered photon. In 3D PET systems, the arc may be rotated 360 degrees about the axis **48** between the two detectors A, B to define a bounded volume. In 2D PET systems, the two arcs **40**, **45** may define a first annihilation area bounded by the two arcs **40**, **45**.

In addition to the two arcs, the PET system may also determine a second annihilation area **46** that is bounded by an outline **47** of the subject's body. This area **46** may generally represent locations within the subject's body, whereas everything outside the outline **47** is located outside the subject's body. Furthermore, the second annihilation area **46** may have certain areas that overlap the first annihilation area defined by the two arcs **40**, **45**. The PET system may determine the second annihilation area **46** by any method now known or later developed. Examples of methods that may be used to determine the second annihilation area **46** may include, but are not limited to, use of an external x-ray source to calculate the attenuation of the subject's body, use of an optical system (e.g., laser-based systems or photogrammetric systems), use of a PET/CT or a PET/MRI system, wherein the CT or the MRI outline is used, approximating the subject outline based on an early iteration without subject outline constraints, or use of a geometric shape (e.g., an ellipsis) that encompasses the subject, wherein the size of the geometric shape may be chosen based on a measurement or an estimation of the size of the subject.

Since the annihilation event can only happen within the body of the subject, the PET system may recognize any number of possible annihilation event locations inside the second annihilation area **46** and discard any possible annihilation event locations that are outside the annihilation area **46**. Furthermore, the PET system may recognize that the annihilation event occurred within the area bounded by the two arcs **40**, **45**. The PET system may combine the information obtained and eliminate any possible positions that occur outside the first annihilation area bounded by the two arcs **40**, **45** and the second annihilation area **46**. Thus, areas that are bounded by the two arcs **40**, **45** and not bounded by the subject's body **46**, as well as areas bounded by the subject's body **46** but not bounded by the two arcs **40**, **45** may be eliminated as possible locations of the annihilation event. However, the annihilation area **44** that is bounded by the two arcs **40**, **45** and the subject's body **46** may be recognized as containing the annihilation point.

In addition to area defined by the two arcs **40**, **45** and the second annihilation area **46**, the PET system may further narrow the area containing the annihilation point by drawing a plurality of straight lines between the point where the unscattered photon is detected to each locus of an intersection of the two arcs **40**, **45** with the outline **47** of the subject's body. In the example shown in FIG. **3**, each locus of the intersection of the two arcs **40**, **45** and the outline **47** of the subject's body both occur on arc **40**. However, it is anticipated that each locus may occur on either arc, or even both arcs. Thus, the two lines **41**, **42** extend from the point of detection on Detector A to each intersection of the outline **47** and the arc **40**. As a result, a third annihilation area **43** is

7

8

formed. The PET system may recognize that the exact location of the annihilation event will be within the third annihilation area **43**. Thus, the PET system may use that information in conjunction with one or more reconstruction algorithms to further attempt to discern an exact location of the annihilation event, as described in more detail herein.

In an embodiment, a Compton equation may be used to determine a scattering angle, which, in turn, may be used to determine two symmetrically circular arcs (TCA) that extend between the two detectors sensing a pair of coincident photons, wherein one photon is scattered and the other remains unscattered. The Compton equation for a PET system is as follows:

$$E_s = \frac{E}{2 - \cos\theta}$$

where E_s is the scattered photon energy, E is the unscattered photon energy (0.511 MeV), and θ is the scattering angle of the unscattered photon.

The size and shape of the area encompassed by the TCA is a function of the scattering angle and the detector position. In the limit where the scattering angle approaches zero and the energy of the scattered photon approaches 511 keV, the shape of the area encompassed by the TCA approaches the LOR for unscattered photons. This approach therefore does not distinguish explicitly between scattered and unscattered photons.

FIG. **4** depicts a circular arc $\overline{SD}$ that is created by a PET system in measuring all of the possible locations of a point of scatter of a scattered photon, in accordance with an embodiment.

M may represent a midpoint of line SD wherein the coordinates of midpoint M are represented by equations (1) and (2):

$$x_0 = \frac{x_1 + x_2}{2} \tag{1}$$

$$y_0 = \frac{y_1 + y_2}{2} \tag{2}$$

Furthermore, a straight line distance between S and D may be calculated as shown in Equation (3):

$$SD = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{3}$$

In addition, circle O (where O represents the center of the circle) may have a radius represented by Equation (4):

$$r = \frac{SD}{2\sin\omega} \tag{4}$$

Using the above equations, it can be shown that line SD and line OM are perpendicular to each other, as illustrated in Equation (5):

$$(x_1 - x_2)(o_1 - x_0) + (y_1 - y_2)(o_2 - y_0) = 0 \tag{5}$$

Furthermore, the length of line OM is represented by Equation (6):

$$OM = \sqrt{(o_1 - x_0)^2 + (o_2 - y_0)^2} = r^* \cos \omega \tag{6}$$

In instances where X_1 is not equal to X_2, the coordinates of the center of the circle O may be represented by Equations (7) and (8), or alternatively by Equations (9) and (10):

$$o_1 = x_0 - \frac{(y_1 - y_2) * \cos\omega}{2 * \sin\omega} \tag{7}$$

$$o_2 = y_0 - \frac{(x_1 - x_2) * \cos\omega}{2 * \sin\omega} \tag{8}$$

$$o_1' = x_0 - \frac{(y_1 - y_2) * \cos\omega}{2 * \sin\omega} \tag{9}$$

$$o_2' = y_0 - \frac{(x_1 - x_2) * \cos\omega}{2 * \sin\omega} \tag{10}$$

Conversely, in instances where X_1 is equal to X_2, the coordinates of the center of the circle O may be represented by Equations (11) and (12) or alternatively by Equations (13) and (14):

$$o_1 = x_0 + r^* \cos \omega \tag{11}$$

$$o_2 = y_0 \tag{12}$$

$$o'_1 = x_0 - r^* \cos \omega \tag{13}$$

$$o'_2 = y_0 \tag{14}$$

Thus, the first annihilation area bounded by the two arcs may be represented by Equation (15):

$$(x - o_1)^2 + (y - o_2)^2 \le r^2 \& (x - o'_1)^2 + (y - o'_2)^2 \le r^2 \tag{15}$$

FIG. **5** depicts an alternative measurement of circular arc $\overline{SD}$ that is created by a PET system in measuring all of the possible locations of a point of scatter of a scattered photon, in accordance with another embodiment. M may represent a midpoint of line SD and may have coordinates as shown in Equations (1) and (2). In this embodiment, P may represent any point in the plane. Thus, the length of line PM may be calculated by Equation (16):

$$PM = \sqrt{(x_1 - x_0)^2 + (y_1 - y_0)^2} \tag{16}$$

Line PM and line SD may define an angle, as represented by Equation (17):

$$\cos\psi = \frac{|(x - x_0)(x_1 - x_2) + (y - y_0)(y_1 - y_2)|}{\sqrt{(x - x_0)^2 + (y - y_0)^2} * \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}} \tag{17}$$

Thus, when drawing a line from point P to point Q on line SD, wherein the PQ is perpendicular to SD, the length of line PQ can be calculated with Equation (18):

$$PQ = PM^* \sin \psi \tag{18}$$

Furthermore the length of line QM can be calculated with Equation (19):

$$QM = PM^* \cos \psi \tag{19}$$

Thus, the length of line SD is found by use of Equation (20):

$$SD = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \tag{20}$$

From Equation (20), the radius of circle **0** can be found with Equation (21):

$$r = \frac{SD}{2\sin\omega} \tag{21}$$

Then, as depicted in FIG. **6**, the arc is rotated so that line SD is located upon the x-axis at a location that allows point the middle point M to be located at the origin (0,0). Thus, the coordinates of S' are (−SD/2, 0) and the coordinates of D' are (SD/2, 0). The coordinates of the center of the circle **0** are (0, −r×cos ω), where ω represents the scattering angle created by the γ axis and line OD. Since point P' is located on the circle O, the coordinates for point P' may be calculated using Equation (22):

$$x^2 + (y + r^* \cos \omega)^2 = r^2 \qquad (22)$$

Accordingly, the length of line P'Q' can be found with Equation (23):

$$P'Q' = y = \sqrt{r^2 - x^2} - r^* \cos \omega \qquad (23)$$

The other root of the equation may be ignored because of its physical meaning, thereby the constraint for any point P in the plane located within the two circular arcs giving Equation (24):

$$PQ \le \sqrt{r^2 - QM^2} - r^* \cos \omega \qquad (24)$$

In yet another alternative embodiment, a calculation of a circular arc that is created by a PET system in measuring all of the possible locations of a point of scatter of a scattered photon may involve first assuming that the two detectors that detect the photons are defined by angles Ω_1 and Ω_2 on a circle of radius R about an origin O. The length of a chord that connects the two detectors may be given be Equation (25):

$$2R \sin\left(\frac{\Omega_2 - \Omega_1}{2}\right) \qquad (25)$$

If the same chord that connects the two detectors is labeled 2U, then Equation (25) is rewritten as Equation (26):

$$U = R \sin\left(\frac{\Omega_2 - \Omega_1}{2}\right) \qquad (26)$$

Thus, a vector drawn from the origin O to the center of the chord may have a magnitude given by Equation (27):

$$r_1 = R \cos\left(\frac{\Omega_2 - \Omega_1}{2}\right) \qquad (27)$$

That vector V, may further be given in radial coordinates $V_1(r_1, \phi)$ by Equation (28):

$$V_1\left(R \cos\left(\frac{\Omega_2 - \Omega_1}{2}\right), \frac{\Omega_2 - \Omega_1}{2}\right) \qquad (28)$$

The implicit equation in (x,y) which describes the two circular arcs in terms of the scattering angle θ and the radial distance between the detectors U when the center of the two circular arcs is located at the origin O is given by Equation (29):

$$\theta = \pi - \arctan\left(\frac{U - y}{x}\right) - \arctan\left(\frac{U + y}{x}\right) \qquad (29)$$

The relationship between the scattering angle θ and the scattered photon energy E_s in a PET system is given by Equation (30):

$$E_s = \frac{E}{2 - \cos\theta} \qquad (30)$$

Solving for θ gives Equation (31):

$$\theta = \left\{ \pi - \arccos \frac{1}{E_s}(E - 2E_s) + 2\pi k \mid k \in Z \right\} \qquad (31)$$

which allows for a relation of the equation describing the x, y position of the two circular arcs to the scattered photon by Equation (32):

$$\arccos \frac{1}{E_s}(E - 2E_s) = \arctan\left(\frac{U - y}{x}\right) - \arctan\left(\frac{U + y}{x}\right) \qquad (32)$$

Writing Equation (32) in radial coordinates $V_2(r_2, \tau)$ where tan

$$\tau = \frac{x}{y} \text{ and } r_2 = \sqrt{x^2 + y^2} = x\sqrt{1 + \frac{1}{\tan^2\tau}}$$

gives Equation (33):

$$\arccos \frac{1}{E_s}(E - 2E_s) = \qquad (33)$$

$$\arctan\left(\frac{U\sqrt{1 + \frac{1}{\tan^2\tau}}}{r^2} - \frac{1}{\tan\tau}\right) + \arctan\left(\frac{U\sqrt{1 + \frac{1}{\tan^2\tau}}}{r^2} + \frac{1}{\tan\tau}\right)$$

When Equation (33) is solved for r_2 and by substituting for U, Equation (34) results:

$$r_2 = \frac{1}{2}RE_s\left(\sin\left(\frac{\Omega_1 - \Omega_2}{2}\right)\right)\frac{\tan^2\tau - 1}{\tan^4\tau - 1}\sqrt{-\frac{1}{E_s^2}(E^2 - 4EE_s + 3E_s^2)}^{2} \quad (X) \qquad (34)$$

$$X = \frac{\sqrt{-(\tan^2\tau + 1)(E^2 - 4EE_s - E_s^2\tan^2\tau)} + 2E(\tan^2\tau)\sqrt{\frac{1}{\tan^2\tau}(\tan^2\tau + 1)} - 4E_s(\tan^2\tau)\sqrt{\frac{1}{\tan^2\tau}(\tan^2\tau + 1)}}{E^2 - 4EE_s + 3E_s^2}$$

The vector V_2 which describes the vector from the center of the chord to the circular arc is given by $V_2(r_2, \tau)$. Summing the vectors V_1 and V_2 enables the two circular arcs to be calculated for any pair of detected photons and scattered photon energy.

Accordingly, the PET system may recognize that the annihilation point may be positioned at a location that is within the area (2D systems) or volume (3D systems) bounded by the arcs **40**, **45** and the area bounded by the subject's body **46**, as shown in FIG. **3**. Thus, in instances where an annihilation event has produced a scattered photon

and an unscattered photon, and further wherein Detector A detects the scattered photon and Detector B detects the unscattered photon, the PET system will measure the energies of the two photons to create a model containing the arcs **40**, **45** and determine that the annihilation event occurred at a location along LOR **49** within the third annihilation area **43**.

FIG. **7** depicts a flow diagram of a process used according to an embodiment to detect photons produced from an annihilation. A first step may be to position the detectors **105**. Positioning may be in any manner necessary to obtain a desired scan of a target object. Once the detectors have been positioned, the location of the detectors may be recorded **110** so that locations of annihilations, as described herein, can be located with respect to the detectors.

Once the detectors have been positioned and their locations have been recorded, the PET system may begin detecting incoming photon activity **115**. Thus, each time a detector senses a photon, the system may record information about the photon **120**. Information about the photon may include, but is not limited to, a time at which the photon was detected, a location of the detector when the photon was detected, a location on the detector where the photon was sensed, an energy produced by the photon and/or the like.

The PET system may compare the detection times of the detected photons and make a determination as to whether a given pair of photons are coincident **125**. This determination may be based upon a matching process, wherein a pair of photons that are detected at substantially the same time may be deemed coincident. Additionally, photons that are detected within about 4.5 nanoseconds to about 12 nanoseconds of each other may be deemed to be sufficiently coincident to be matched as a pair. In an embodiment, photons that are detected within about 5 nanoseconds of each other may be deemed to be sufficiently coincident to be matched as a pair. In another embodiment, photons that are detected within about 7.5 nanoseconds of each other may be deemed to be sufficiently coincident to be matched as a pair. In another embodiment, photons that are detected within about 10 nanoseconds of each other may be deemed to be sufficiently coincident to be matched as a pair. The system may continue to detect additional incoming photons, and may optionally reposition the detectors and record their new locations **130**.

If a pair of photons has been deemed coincident, the PET system may analyze the recorded energies of the photons, which may optionally be retrieved from memory **135**. The system may initialize an image matrix **140**, which provides starting values for a scanned image. The image matrix may generally be, for example, a mathematical matrix, wherein each pixel of the image is initially set to a value. As the reconstruction progresses, the image is updated to represent the distribution of activity. The sizes of the matrix may reduce any computation burden and increase any spatial resolution.

Using the image matrix, the PET system may begin the image reconstruction process by first calculating the scattering angle for each pair of coincident photons **145**, as described in more detail herein. With the scattering angle calculated, the PET system may then identify the circular arcs from the measured energies of the photons **150**. The PET system may also construct a boundary line around the subject's body **152** and then construct one or more lines from the detection point of the unscattered photon to the intersection of the circular arcs with the boundary line **153**. The area (2D systems) or the volume (3D systems) bounded

by the arcs, the subject's body boundary and the one or more lines may be used to identify possible annihilation points therein **155**.

Armed with the information regarding the location of possible annihilation points, the system may use one or more reconstruction algorithms **160** now known or later developed to further narrow the possibilities for annihilation point locations and reconstruct the image. Examples of reconstruction algorithms may include, but are not limited to, a Maximum-Likelihood Expectation-Maximum (MLEM) algorithm, an ordered subset expectation maximization (OSEM) algorithm, a maximum a posteriori expectation maximization (MAPEM) algorithm, a filtered back projection (FBP) algorithm, a conjugate gradient (CG) algorithm and a coincidence-list-ordered sets expectation-maximization (CLOSEM) algorithm.

The location of each annihilation point may be estimated from each pair of coincident photons (whether scattered or unscattered) and by using one or more reconstruction algorithms, the PET system may reconstruct a distribution of activity. If the reconstruction is carried out using a Maximum-Likelihood Expectation-Maximum (MLEM) Algorithm, this process may include the normalization of the image matrix, and the back-projection of the sum of the pixel values with the annihilation areas for each coincident pair of photons into a ratio matrix **165**. The ratio matrix may store a backprojected value for each pair of photons in each iteration. After all of the pairs have been calculated, the ratio matrix may be used to update the image matrix. The ratio matrix may be re-initialized (i.e., set to zero), and the process may repeat. The reconstructed image may then be updated with the new information **175**, and the PET system may then make a determination as to whether convergence has been obtained **180**. Convergence may be obtained by any methods of estimation now known or later developed. One such example of a method may include evaluating noise level of an image and stop iterating once the noise level has reached a minimum threshold.

If convergence has not been obtained, the system may use one or more additional reconstruction algorithms **160** and repeat the process. If convergence has been obtained, the image may be outputted **185** to a device that is operably connected to the PET system, such as, for example, a computer monitor, a printer and/or the like.

FIG. **8** depicts an illustrative cross-sectional view of a PET system **190**. The PET system **190** may generally have a plurality of detectors **192** arranged in a circular manner about a subject **194**, such as a system where the detectors **192** are arranged on the inside surface of a cylindrical structure, and the subject **194** is placed within the cylinder so that the detectors **192** surround the subject **193** on all sides. Each of the detectors **192** may further be rotatable around the subject **194**. Thus, each of the detectors **192** may have an ability to obtain readings, as described in more detail herein, at any position 360 degrees around the subject **194**. While the detectors **192** shown herein are rectangular in shape, those skilled in the art will recognize that the detectors **192** may be any shape without departing from the scope of this disclosure. The detectors **192** may further be connected to a number of other components, such as the components disclosed in FIG. **9**.

FIG. **9** depicts a block diagram of illustrative internal hardware that may be used to contain or implement program instructions, such as the process steps discussed above in reference to FIG. **7**, according to embodiments. A bus **200** serves as the main information highway interconnecting the other illustrated components of the hardware. CPU **205** is

the central processing unit of the system, performing calculations and logic operations required to execute a program. The CPU **205**, alone or in conjunction with one or more of the other elements disclosed herein, is an illustrative processing device, computing device or processor as such terms are used within this disclosure. Read only memory (ROM) **220** and random access memory (RAM) **225** constitute illustrative memory devices (i.e., processor-readable non-transitory storage media).

A controller **210** interfaces with one or more optional memory devices **215** to the system bus **200**. These memory devices **215** may include, for example, an external or internal DVD drive, a CD ROM drive, a hard drive, flash memory, a USB drive or the like. As indicated previously, these various drives and controllers are optional devices.

Program instructions, software or interactive modules for providing the interface and performing any querying or analysis associated with one or more data sets may be stored in the ROM **220** and/or the RAM **225**. Optionally, the program instructions may be stored on a tangible computer readable medium such as a compact disk, a digital disk, flash memory, a memory card, a USB drive, an optical disc storage medium, such as a Blu-ray™ disc, and/or other non-transitory storage media.

An optional display interface **255** may permit information from the bus **200** to be displayed on the display **260** in audio, visual, graphic or alphanumeric format. Communication with external devices, such as a print device, may occur using various communication ports **245**. An illustrative communication port **245** may be attached to a communications network, such as the Internet or an intranet.

The hardware may also include an interface **230** which allows for receipt of data from input devices such as a keyboard **240** or other input device **235** such as a mouse, a joystick, a touch screen, a remote control, a pointing device, a video input device and/or an audio input device.

The hardware may also include one or more detectors **250** connected to the bus **200**, which allow the system to detect photon activity, as described in more detail herein. The one or more detectors **250** may optionally be connected to the communications ports **245** in instances where the hardware is employed at a location that is remote to the location of the detectors **250**.

In the above detailed description, reference is made to the accompanying drawings, which form a part hereof. In the drawings, similar symbols typically identify similar components, unless context dictates otherwise. The illustrative embodiments described in the detailed description, drawings, and claims are not meant to be limiting. Other embodiments may be used, and other changes may be made, without departing from the spirit or scope of the subject matter presented herein. It will be readily understood that the aspects of the present disclosure, as generally described herein, and illustrated in the Figures, can be arranged, substituted, combined, separated, and designed in a wide variety of different configurations, all of which are explicitly contemplated herein.

The present disclosure is not to be limited in terms of the particular embodiments described in this application, which are intended as illustrations of various aspects. Many modifications and variations can be made without departing from its spirit and scope, as will be apparent to those skilled in the art. Functionally equivalent methods and apparatuses within the scope of the disclosure, in addition to those enumerated herein, will be apparent to those skilled in the art from the foregoing descriptions. Such modifications and variations are intended to fall within the scope of the appended claims.

The present disclosure is to be limited only by the terms of the appended claims, along with the full scope of equivalents to which such claims are entitled. It is to be understood that this disclosure is not limited to particular methods, reagents, compounds, compositions or biological systems, which can, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting.

With respect to the use of substantially any plural and/or singular terms herein, those having skill in the art can translate from the plural to the singular and/or from the singular to the plural as is appropriate to the context and/or application. The various singular/plural permutations may be expressly set forth herein for sake of clarity.

It will be understood by those within the art that, in general, terms used herein, and especially in the appended claims (e.g., bodies of the appended claims) are generally intended as "open" terms (e.g., the term "including" should be interpreted as "including but not limited to," the term "having" should be interpreted as "having at least," the term "includes" should be interpreted as "includes but is not limited to," etc.). While various compositions, methods, and devices are described in terms of "comprising" various components or steps (interpreted as meaning "including, but not limited to"), the compositions, methods, and devices can also "consist essentially of" or "consist of" the various components and steps, and such terminology should be interpreted as defining essentially closed-member groups. It will be further understood by those within the art that if a specific number of an introduced claim recitation is intended, such an intent will be explicitly recited in the claim, and in the absence of such recitation no such intent is present. For example, as an aid to understanding, the following appended claims may contain usage of the introductory phrases "at least one" and "one or more" to introduce claim recitations. However, the use of such phrases should not be construed to imply that the introduction of a claim recitation by the indefinite articles "a" or "an" limits any particular claim containing such introduced claim recitation to embodiments containing only one such recitation, even when the same claim includes the introductory phrases "one or more" or "at least one" and indefinite articles such as "a" or "an" (e.g., "a" and/or "an" should be interpreted to mean "at least one" or "one or more"); the same holds true for the use of definite articles used to introduce claim recitations. In addition, even if a specific number of an introduced claim recitation is explicitly recited, those skilled in the art will recognize that such recitation should be interpreted to mean at least the recited number (e.g., the bare recitation of "two recitations," without other modifiers, means at least two recitations, or two or more recitations). Furthermore, in those instances where a convention analogous to "at least one of A, B, and C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, and C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). In those instances where a convention analogous to "at least one of A, B, or C, etc." is used, in general such a construction is intended in the sense one having skill in the art would understand the convention (e.g., "a system having at least one of A, B, or C" would include but not be limited to systems that have A alone, B alone, C alone, A and B together, A and C together, B and C together, and/or A, B, and C together, etc.). It will be further understood by those within the art that virtually any disjunctive

word and/or phrase presenting two or more alternative terms, whether in the description, claims, or drawings, should be understood to contemplate the possibilities of including one of the terms, either of the terms, or both terms. For example, the phrase "A or B" will be understood to include the possibilities of "A" or "B" or "A and B."

In addition, where features or aspects of the disclosure are described in terms of Markush groups, those skilled in the art will recognize that the disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group.

As will be understood by one skilled in the art, for any and all purposes, such as in terms of providing a written description, all ranges disclosed herein also encompass any and all possible subranges and combinations of subranges thereof. Any listed range can be easily recognized as sufficiently describing and enabling the same range being broken down into at least equal halves, thirds, quarters, fifths, tenths, etc. As a non-limiting example, each range discussed herein can be readily broken down into a lower third, middle third and upper third, etc. As will also be understood by one skilled in the art all language such as "up to," "at least," and the like include the number recited and refer to ranges which can be subsequently broken down into subranges as discussed above. Finally, as will be understood by one skilled in the art, a range includes each individual member. Thus, for example, a group having 1-3 cells refers to groups having 1, 2, or 3 cells. Similarly, a group having 1-5 cells refers to groups having 1, 2, 3, 4, or 5 cells, and so forth.

Various of the above-disclosed and other features and functions, or alternatives thereof, may be combined into many other different systems or applications. Various presently unforeseen or unanticipated alternatives, modifications, variations or improvements therein may be subsequently made by those skilled in the art, each of which is also intended to be encompassed by the disclosed embodiments.

What is claimed is:

1. A method of reconstructing an image from a positron emission tomography scan, comprising:
   detecting a pair of photons by a plurality of detectors, wherein the pair of photons comprises a first photon and a second photon;
   measuring, by the plurality of detectors, an energy produced by each of the pair of photons;
   calculating, by a processing device, a first arc and a second arc between detector locations based on the energy produced by each of the pair of photons;
   determining, by the processing device, a first annihilation area bounded at least in part by the first arc and the second arc, wherein the first annihilation area indicates a plurality of possible locations of an annihilation point from which the pair of photons originated; and
   reconstructing, by the processing device, an image using a reconstruction algorithm, wherein the reconstruction algorithm uses information regarding the first annihilation area.

2. The method of claim 1, wherein the calculating further comprises:
   calculating the first arc based on the energy produced by the first photon of the pair of photons; and
   calculating the second arc based on the energy produced by the second photon of the pair of photons.

3. The method of claim 1, further comprising:
   identifying a plurality of possible locations of the annihilation point within the first annihilation area.

4. The method of claim 3, further comprising:
   using the reconstruction algorithm to identify a second plurality of possible locations of the annihilation point;
   matching the plurality of possible locations of the annihilation point within the first annihilation area with the second plurality of possible locations of the annihilation point identified from the reconstruction algorithm; and
   from the matching, determining an actual location of the annihilation point.

5. The method of claim 3, wherein the identifying a plurality of possible locations of the annihilation point within the first annihilation area decreases a sensitivity of the positron emission tomography scan to the scattered photons.

6. The method of claim 1, further comprising:
   identifying a second annihilation area bounded by a subject outline; and
   identifying the plurality of possible locations of the annihilation point within both the first annihilation area and the second annihilation area bounded by the subject outline.

7. The method of claim 1, wherein the measuring further comprises:
   constructing an outline of a subject;
   constructing one or more lines from a point of detection of an unscattered photon of the pair of photons to each intersection of the outline of the subject with the first arc or the second arc;
   identifying a second annihilation area bounded by three or more of the following: the one or more lines, the outline of the subject, and one of the first arc or the second arc; and
   identifying the plurality of possible locations of the annihilation point within the second annihilation area.

8. The method of claim 1, wherein the reconstruction algorithm comprises a Maximum-Likelihood Expectation-Maximum algorithm.

9. The method of claim 1, wherein the reconstruction algorithm comprises an ordered subset expectation maximization algorithm.

10. The method of claim 1, wherein the reconstruction algorithm comprises a maximum a posteriori expectation maximization algorithm.

11. The method of claim 1, wherein the reconstruction algorithm comprises a filtered back projection algorithm.

12. The method of claim 1, wherein the reconstruction algorithm comprises a conjugate gradient algorithm.

13. The method of claim 1, wherein the reconstruction algorithm comprises a coincidence-list-ordered sets expectation-maximization algorithm.

14. The method of claim 1, further comprising:
   based on the energy produced, determining a scattering angle for the pair of photons from the annihilation point relative to the position of the plurality of detectors; and
   determining the first arc and the second arc based on the scattering angle, and wherein the first arc and the second arc are circular arcs.

15. The method of claim 1, wherein the detector locations comprises a first detector location at which the first photon of the pair of photons was detected and a second detector location at which the second photon of the pair of photons was detected.

16. A system for use in reconstructing an image from a positron emission tomography scan, wherein the system comprises:

a processing device; and

a non-transitory computer-readable storage medium in communication with the processing device,

wherein the computer-readable storage medium contains one or more programming instructions that, when executed, cause the processing device to:

measure an energy produced by a first photon and a second photon of a pair of photons;

calculate a first arc and a second arc between detector locations based on the energy produced by each of the pair of photons;

determine a first annihilation area bounded at least in part by the first arc and the second arc, wherein the first annihilation area indicates a plurality of possible locations of an annihilation point from which the pair of photons originated; and

reconstruct an image using a reconstruction algorithm, wherein the reconstruction algorithm uses information regarding the first annihilation area.

17. The system of claim 16, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, further causes the processing device to:

calculate a first arc based on the energy produced by the first photon of the pair of photons;

calculate a second arc based on the energy produced by the second photon of the pair of photons;

identify a plurality of possible locations of the annihilation point within the first annihilation area.

18. The system of claim 17, further comprising a plurality of detectors configured to detect photons, wherein the plurality of detectors further comprises a plurality of energy sensitive detectors.

19. The system of claim 18, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, further causes the processing device to:

direct the plurality of energy sensitive detectors to measure the energy produced by a plurality of scattered photons from an annihilation event.

20. The system of claim 17, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, further causes the processing device to:

use the reconstruction algorithm to identify a second plurality of possible locations of the annihilation point;

match the plurality of possible locations of the annihilation point within the first annihilation area with the

second plurality of possible locations of the annihilation point identified from the reconstruction algorithm; and

from the matching, determine an actual location of the annihilation point.

21. The system of claim 16, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, further causes the processing device to:

identify a second annihilation area bounded by a subject outline; and

identify a second plurality of possible locations of the annihilation point within the second annihilation area.

22. The system of claim 16, wherein the computer-readable storage medium contains one or more programming instructions that, when executed, further causes the processing device to:

construct an outline of a subject;

construct one or more lines from a point of detection of an unscattered photon of the pair of photons to each intersection of the outline of the subject with the first arc or the second arc;

identify a second annihilation area bounded by the first arc, the second arc, and at least one of the one or more lines and the outline of the subject; and

identify the plurality of possible locations of the annihilation point within the second annihilation area.

23. The system of claim 16, wherein the identifying a plurality of possible locations of the annihilation point within the first annihilation area decreases a sensitivity of the positron emission tomography scan to the scattered photons.

24. The system of claim 16, wherein the reconstruction algorithm comprises a Maximum-Likelihood Expectation-Maximum algorithm.

25. The system of claim 16, wherein the reconstruction algorithm comprises an ordered subset expectation maximization algorithm.

26. The system of claim 16, wherein the reconstruction algorithm comprises a maximum a posteriori expectation maximization algorithm.

27. The system of claim 16, wherein the reconstruction algorithm comprises a filtered back projection algorithm.

28. The system of claim 16, wherein the reconstruction algorithm comprises a conjugate gradient algorithm.

29. The system of claim 16, wherein the reconstruction algorithm comprises a coincidence-list-ordered sets expectation-maximization algorithm.

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